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Assessment of tree seed oil biodiesel: A comparative review based on biodiesel of a locally available tree seed

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ABSTRACT

The present investigation is undertaken to investigate prospect of seeds of a locally available tree (koroch) for biodiesel production. The middle-size, evergreen koroch tree with spreading branches are available in Assam. The characteristics of koroch biodiesel and engine performance fueled by koroch biodiesel are also analyzed reviewing similar results available in the literature so as to ascertain its status. Twelve number of different tree seed oils, reported earlier, are considered for making the present comparative assessment. Though transesterification has been the common process for converting tree seed oil into biodiesel, as evidenced from the literature consulted in this study, but there have been variations of the chemical processes. Variations of the transesterification are attributed to (i) types of catalysis viz., acid (H_2SO_4) or base (KOH, NaOH, and $NaOCH_3$), (ii) reaction temperature, (iii) molar ratio, (iv) nature of reaction viz., single stage or multi-stage. The outputs of the reaction have also been found varying in terms of yield as well as quality. Quality of biodiesel, however, was found to influence by the nature of feedstock. The assessment of quality parameters was made either by ASTM D 6751 or EN 14214 standards. The major fuel properties such as calorific value, kinematic viscosity, cetane number and cloud point of the reference biodiesel (koroch biodiesel) are compared with the properties of five biodiesel obtained from non-edible tree seed (karanja, mahua, polonga, jatropha and rubber seed) and then ranked them in order of desirable property. No single biodiesel type could be found at top rank with reference to more than one property. With regards to viscosity, except rubber seed biodiesel, all other biodiesels (karanja, mahua, polonga, jatropha and koroch) fulfilled the ASTM D 6751 (1.9–6 cSt) as well as EN14214 (3.5–5) standards. Koroch biodiesel ranks 3rd, 3rd and 6th in case of kinematic viscosity, cetane number and calorific value amongst the biodiesel types considered for the present study. Cloud point of koroch, polanga, mahua, rubber, karanja and jatropha biodiesels are 4, 13.2, 5, 4, 12 and 4 °C. Further, properties of biodiesel were found to have influencing correlation with the fatty acid characteristics of the feedstock. Therefore, biodiesel with desirable properties could be expected form optimum mixing of different feedstock.

Eleven number of different engine performance results pertaining to uses of biodiesel are also reviewed in this paper. Varying test conditions with reference to fuel types and blends, engine size and loading pattern are discussed. Engine performance results of koroch biodiesel were then compared with five similar tree-based biodiesel. It is observed that tree seed oil with more unsaturated fatty acids exhibits lower thermal efficiency compared to biodiesel having more saturated acids.

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1. Introduction

India consumed nearly 3 million barrels per day (mbd), making it fourth largest consumer of petroleum oil in the world, 70% of which (2.1 mbd) were imported. The combination of rising oil consumption and relatively flat domestic production has left India increasingly dependent on imports to meet its petroleum demand. As per the projected estimates of Energy Information Administration (EIA), India would become the fourth largest net importer of oil in the world by 2025, behind the United States, China, and Japan. The consumption of liquid petroleum products, especially diesel fuel, has grown up significantly due to growth of major economical sectors viz., transport, agriculture and industry. But, the excessive dependency on export grade fuel and limitations associated with fossil fuel become a concern for desired economic growth in India. To reduce the uncertainties associated with the petro-diesel, Government of India, like other nations of the world, have made plan to promote alternative sustainable fuels. With the current level of research and development works, biodiesel has been found as a viable sustainable substitute for petroleum diesel.

The vegetable oil, animal fat and waste cooking oil are generally targeted as feedstock for biodiesel production. However, there are several region specific factors governing the selection of feedstock. For example, country like India cannot spare edible vegetable oil for biodiesel production, due to obvious reason of food shortage. As per report, more that 4.0 million tones of vegetable oil were imported by India to fulfill the domestic requirements during 2008–2009. Moreover, the diversion of crop land for biodiesel production is also not practical in Indian context. Thus, the identification of non-farm vegetable oil sources for biodiesel production is considered ideal in Indian situation.

India has a vast land area devoted for different types of forestry. Some of the forest trees have already been identified as prospective sources for biodiesel production [1–20]. Karanja (*Pongamia pinnata*), koroch (*Pongamia glabra*), neem (*Azadirachta indica*), ratanjot (*Jatropha curcas*), mahua (*Madhuca longifolia*), polanga (*Calophyllum inophyllum*), rubber (*Hevea brasiliensis*), jojoba (*Simmondsia chinensis*), linseed (*Linum usitatissimum*) [3,5,7–10,15–18,20], available in Indian forests, are getting R&D attention for biodiesel production. However, in spite of such research efforts, large scale utilization through commercial routes is yet to start in India. It impels the requirements of target oriented and region specific research efforts so as to assist the implementation of the policy of Government of India on biofuel including biodiesel. The state of Assam situated in the northeastern part of India has about 33% of land under forest. A variety of indigenous oil seeds bearing plants grow well in their natural habitats of Assam forest. Promotion of suitable tree species as prospective feedstock for biodiesel production in line with the government policy is expected to address several socio-economic issues of this region. The present investigation is undertaken to investigate prospect of seeds of a locally available tree (koroch, *P. glabra* Vent.) for biodiesel production. Further, the characteristics of koroch biodiesel and engine performance fueled by koroch biodiesel are also analyzed reviewing similar results available in the literature so as to ascertain its status.

2. Description of koroch tree

The middle-size, evergreen koroch tree with spreading branches are commonly available in Lakhimpur, Sibsagar, Dibrugarh, Darrang, Kamrup and Nagoan districts of Assam [21]. Wood of koroch is hard and heavy and yellowish in colour. A fully mature tree produces up to 50 kg of seeds yearly with about 33.6% oil content. In addition to the dominant uses of the koroch wood as cooking fuel, the seed and bark have traditional medicinal uses [21].

3. Methods and materials

Batch stirred reactor of 1 L volume is used for preparation of biodiesel from koroch seeds collected from the forest of Assam using transesterification [17]. Batch stirred reactor consists of three necks for stirrer, condenser and inlet of reactant as well as for placing the thermocouple to observe the reaction temperature. The flask has a stopcock at the bottom for collection of the final product. Process parameters such as reaction temperature, reaction duration, stirring speed, amount of catalyst and volume of methanol were optimized in 1 L batch stirred reactor. The optimized parameters were used for large quantity production of biodiesel in 50 L capacity per batch biodiesel pilot plant for engine performance and emission. Part of the biodiesel is used to determine its characteristics. Remaining part is used to prepare blends with petro-diesel for investigating engine performance. The detail procedure of investigating fuel characteristics and engine performance are given below.

3.1. Methodology for analyzing fuel characteristics of koroch biodiesel and its comparison with biodiesel produced from similar feedstock

The fatty acid composition of the koroch oil was determined using a Gas Chromatograph (Thermo Electron Corporation) series equipped with Flame Ionization Detector (FID) at Centre for Rural Development and Technology of Indian Institute of Technology Delhi. Similarly, density (using digital densitometry, ASTM D 4052), kinematic viscosity (using U tube viscometer, ASTM D 445), flash point (using Pensky Martens apparatus, ASTM D 93), pour point and cloud point (ASTM D 97/2500), Copper Strip Corrosion property (ASTM D 130), acid value (ASTM D 974), ash content (using muffle furnace, ASTM D 482), carbon residue (ASTM D 524/ASTM D 4530), moisture content (831K F Coulometer, ASTM D 2709) and calorific value (Bomb Calorimeter, ASTM D 240) are also determined at laboratories of the Indian Institute of Technology Delhi.

Cetane number (CFR engine, ASTM D 613), phosphorus content (ASTM D 4951), free glycerin (Gas Chromatograph, ASTM D 6584) and total glycerin (Gas Chromatograph, ASTM D 6584) are determined at Indian Oil Corporation (R & D), Faridabad, India.

Table 1
Description of biodiesel research considered for the present study.

Sl no.	Name of feedstock	Processing method	Molar ratio, catalyst used	Mechanical stirring speed (rpm)	Temperature of reaction, reaction time	Yield	Year of investigation, region of investigation	Standards	Literature source	Remarks
1a	Karanja oil	Two step transesterification	8:1 for first step/9.1 for second step 1 mL H_2SO_4 for first step/0.5 wt.% catalyst NaOH/KOH for second step	1100	45 °C for both first and second step, 30 min for both first and second step	89.5%	2007 Varanasi, India	Viscosity and acid value satisfied both American and European standards	Sharma and Singh [4]	NaOH was found to be a better catalyst than KOH in terms of yield
1b	Karanja oil	Single step transesterification	6:1, 1% KOH	360	65 °C, 3 h	97–98%	2006 Delhi, India	No information is available about the property and standards of biodiesel	Meher et al. [15]	The reaction was incomplete with a low rate of stirring, i.e. at 180 rpm
1c	Karanja oil	Two step transesterification	6:1 for first step, 0.5% H_2SO_4 for first step	–	–, 1 h for first step	96.6–97%	2008 Delhi, India	Fuel properties satisfied both American and European standards for biodiesel	Naik et al. [17]	Stirring speed, catalyst used, molar ratio used and reaction time for second step are not mentioned
1d	Karanja oil	Two-step transesterification	8 mL methanol for first step/10 mL of methanol for second step, 0.5% (v/v) of sulfuric acid for first step/0.45 g (2%) of KOH for second step	At low stirring speed	45 °C for first step/60 °C for second step, 2 h for second step	80%	2009 USA	Properties of biodiesel produced from karanja oils are comparable to those of the ASTM biodiesel standards	Patil and Deng [11]	Except viscosity (5.52–5.79 mm^2/s) of karanja biodiesel, other properties satisfied European standard also
2a	Jatropha oil	Two-step transesterification	8 mL methanol for first step/10 mL of methanol for second step, 0.5% (v/v) of sulfuric acid for first step/0.45 g (2%) of KOH for second step	At low stirring speed	45 °C for first step/60 °C for second step, 2 h for second step	90–95%	2009 USA	Properties of biodiesel produced from jatropha curcas oils are comparable to those of the ASTM and European biodiesel standards	Patil and Deng [11]	
2b	Jatropha oil	Two-step transesterification	5:1 for second step, acid catalyst (H_2SO_4) for first step/alkaline catalyst (0.55%, w/v KOH)	–	60 °C for second step, ½ h for second step	99%	2007 Kharagpur, India	Properties satisfying the standards for biodiesel	Tiwari et al. [8]	–
2c	Jatropha oil	Two-step transesterification	12 wt% methanol for first step or 20:1 for first step/6:1 for second step, 1 wt% sulfuric acid for first step or 4 wt% solid acid prepared by calcining metatitanic acid/1.3% KOH for second step	–	70 °C for first step or 90 °C for first step/64 °C for second step, 2 h for first step/20 min for second step	98%	2009 PR China	–	Lu et al. [26]	
3	Jatropha curcus oil	Single step transesterification	25% (w/w) methanol, 1% sodium hydroxide (NaOH)	350–400	60 °C, 2 h	82%	2008 Guwahati, India	Properties satisfying the American and European standards for biodiesel	Mahanta et al. [5]	–

Table 1 (*Continued*)

Sl no.	Name of feedstock	Processing method	Molar ratio, catalyst used	Mechanical stirring speed (rpm)	Temperature of reaction, reaction time	Yield	Year of investigation, region of investigation	Standards	Literature source	Remarks
4a	Mahua oil	Three-step transesterification	0.30–0.35 (v/v) methanol-to-oil ratio for first and second step/0.25 (v/v) methanol for third step, 1% (v/v) H_2SO_4 for first and second step/0.7% (w/v) KOH for third step	–	60 °C for first and second steps, 1-h for first and second steps	98%	2005 Kharagpur, India	Fuel properties of conforming to both the American and European standards	Ghadge and Raheman [7]	–
4b	Mahua	Two-step transesterification	0.32 (v/v) methanol for first step/0.25 (v/v) methanol-to-oil ratio (i.e. 6:1 molar ratio) for second step, 1.24% (w/v) H_2SO_4 for first step/0.7% (w/v) KOH for second step	–	60 °C for both first and second step, 1.26 h for first step/1/2 h for second step	98%	2006 Kharagpur, India	Biodiesel properties satisfying both American and European standards for biodiesel	Ghadge and Raheman [12]	–
5a	Pongamia oil	Single step transesterification	210 mL of methanol for 1000 mL of oil, 1.5 wt.% NaOH	–	50 °C, 1.5 h	–	2009 Tamilnadu, India	Cetane number (55.53) is calculated and satisfies biodiesel standards of USA (ASTM D 6751), Germany (DIN V51606) and European Organization (EN 14214)	Eevera et al. [28]	Dynamic viscosity given is 34.66×10^{-6} Ns/m^2
5b	Pongamia pinnata oil	Single step transesterification	1:10 molar ratio of oil to methanol for KOH or solid acid catalyst, 1 wt% (0.1 g)KOH/solid acid catalysts viz. Hb-zeolite, Montmorillonite K-10 and ZnO were also used	–	60 °C for KOH catalyst/120 °C for solid acid catalyst, 24 h for solid acid catalyst	92% or 95% when tetra hydrofuran used as a co-solvent	2005 Chennai, India	Important fuel properties biodiesel satisfied (viscosity = 4.8 cSt at 40 °C and flash point = 150 °C) ASTM, European (EN14214: 2003) and German biodiesel standards (DIN V51606)	Karmee and Chadha [16]	ZnO gave a good conversion of 83%, while Hb-zeolite and Montmorillonite K-10 catalyzed transesterification, gave low conversions of 59% and 47% respectively
5c	Pongamia pinnata oil	Single step transesterification	20% (w/w) methanol, 1% (w/w) NaOH	350–400	60°C, 2 h	75%	2008 Guwahati, India	Except kinematic viscosity (5.75 cSt) all properties satisfying the American and European standards for biodiesel	Mahanta et al. [5]	In European biodiesel standard, kinematic viscosity range for biodiesel is 3.5–5.0 cSt at 40 °C

6	Rubber oil	Two-step transesterification	6:1 for first step, 9:1 for second step, 0.5% of sulfuric acid for first step, 0.5% of NaOH	–	$45 \pm 5\,^{\circ}C$ for both steps, 20–30 min for first step, 30 min for second step	–	2005 Calicut, India	Except viscosity value (5.81 cSt) for European standard, other properties satisfied both American and European standards for biodiesel	Ramadhas et al. [9]	This study supports the production of biodiesel from unrefined rubber seed oil as a viable alternative to the diesel fuel
7	Palm oil	Single step transesterification	15.6:1 (150 mL methanol), sodium hydroxide or sodium metal	–	– –	–	2005 Malaysia	Properties of palm biodiesel such as viscosity, sulfur content and flash point satisfied both ASTM and EN14 214 standards	May et al. [23]	–
8	Tung oil	Single step transesterification	Methanol, KOH	–	$60\,^{\circ}C$, –	88.88%	2010 China	Properties of tung oil biodiesel such as sulfur content and flash point satisfied both ASTM and EN14 214 standards	Qiong Shang et al. [24]	Kinematic viscosity of tung oil biodiesel at $40\,^{\circ}C$ is 7.070 cSt. Kinematic viscosity in ASTM and European standards is 1.9–6 cSt and 3.5–5
9	Camelina oil	Single step transesterification	Oil (180 g, 200 mL, 0.202 mol) and methanol (49 mL, 1.21 mol), 1.0 wt.% $NaOCH_3$	1200	$60\,^{\circ}C$, after 1.5 h of reaction, the mixture was equilibrated to room temperature	89%	2010 USA	Except iodine value (151 $gI_2/100\,g$), all other properties satisfied both American and European standards for biodiesel	Moser and Vaughn [25]	In European standard, iodine value was 120 max. In American standard, it was not specified
10	Jojoba oil-wax	Single step transesterification	7.5:1, sodium metal (0.736 g, 0.032 mol) was added in small pieces to 50 mL of methanol (39.5 g, 1.23 mol) placed in a glass flask in a hood over a period of about 30 min. The solution obtained was used as catalyst	600	$60\,^{\circ}C$, 4 h	55%	2005 Spain	Jojoba biodiesel is close to meet the biodiesel standard EN 14214	Canoira et al. [27]	–
11	Cotton seed oil	Single step transesterification	210 mL of methanol for 1000 mL of oil, 1.5 wt.% NaOH	–	$50\,^{\circ}C$, 1.5 h	–	2009	Cetane number (56.63) is calculated and satisfies biodiesel standards of USA (ASTM D 6751), Germany (DIN V51606) and European Organization (EN 14214)	Eevera et al. [28]	Dynamic viscosity given is $13.27 \times 10^{-6}\,Ns/m^2$
12	Neem	Single step transesterification	210 mL of methanol for 1000 mL of oil, 1.5 wt.% NaOH	–	$50\,^{\circ}C$, 1.5 h	–	2009	Cetane number (52.9) is calculated and satisfies biodiesel standards of USA (ASTM D 6751), Germany (DIN V51606) and European Organization (EN 14214)	Eevera et al. [28]	Dynamic viscosity given is $26.29 \times 10^{-6}\,Ns/m^2$

Biodiesel fuel characteristics are available in literature. In the present study 12 different feedstocks (tree seed oil) reported through 17 standard published sources are considered for review. The details of these 12 feedstocks pertaining processing method and region of investigation, are presented in Table 1. Fuel characteristics results of five oil seed feedstocks viz karanja, mahua, rubber seed, jatropha and polonga pertaining to five Indian studies are used for making comparative assessment of koroch seed oil biodiesel. Five oil seed feedstocks viz karanja, mahua, rubber seed, jatropha and polonga are taken for this study because of region of investigation is India.

Transesterification is the process of separating the fatty acids from their glycerol backbone to form fatty acid esters and free glycerol [15]. Fatty acid esters commonly known as biodiesel can be produced in batches by transesterifying non edible vegetable oil such as karanja, jatropha, neem, rubber seed, tung, palm, jojoba oil wax, cotton seed, camelina with lower molecular weight alcohols (methanol) in presence of a base or an acid catalyst. Transesterification is classified as alkaline catalyzed (single step) and acid-alkaline catalyzed (two step) process. In alkaline catalyzed transesterification process (second step), base catalysts such as sodium methoxide, sodium hydroxide, sodium metal, potassium hydroxide and potassium methoxide are used [4,5,8,11,12,15,22,23,26–28]. Alkaline catalyzed transesterification process is most effective in converting triglycerides into esters when free fatty acid level is less than 1%. It is the most widely used process because it requires only moderate temperatures and lower pressures and also there is high conversion efficiency (98%). This process requires only a small time and there is a direct conversion of biodiesel without any intermediate steps. However, it becomes less effective when the free fatty acid level exceeds 1% because the FFA reacts with the most common alkaline catalysts (NaOH, KOH, and CH_3ONa) and forms soap which inhibit the separation of ester from glycerin and which in turn reduces the conversion rate. Certain amount of alkaline catalyst is consumed in producing soap and hence, catalyst efficiency decreases. In acid transesterification process, acidic catalysts like, sulfuric acid, phosphoric acid, hydrochloric acid, calcining metatitanic acid and organic sulfonic acid are used [4,8,11,12,17,26]. In this process, a strong acid is used as a catalyst for esterification of the FFAs and the transesterification of triglycerides. This process does not yield soap due to the absence of alkali material. The esterification of the FFAs to alcohol esters is relatively fast however; the transesterification of the triglycerides is very slow, taking several days to complete. Another major problem with the use of acid catalyst is the formation of water which stays in the reaction mixture and finally stops the reaction well before reaching the completion. Solid acid catalysts viz. Hb-zeolite, Montmorillonite K-10 and ZnO are also used for production of biodiesel [16]. However, ZnO gave a good conversion of 83%, while Hb-zeolite and Montmorillonite K-10 catalyzed transesterification, gave low conversions of 59% and 47%, respectively.

3.2. Methodology for analyzing performances of engine fueled by koroch biodiesel and their comparison with similar engine test results

3.2.1. Test engine

The test was carried out on a commercial DI, air cooled, single cylinder, four stroke, naturally aspirated constant speed compression ignition engine as per the IS:10,000 [P:5]: 1980. The specifications of the engine are given in Table 2. The engine was coupled to a 5 kVA electric generator through which load was applied by increasing the field voltage shown in Fig. 1. The engine was tested at the rated speed of 1500 rpm only. The engine was started by hand cranking, using decompression lever. The engine was sufficiently warmed up at every stage. The engine emissions were measured with a portable pollution monitor of AVL make; model 4000 Di-Gas Analyzer shown in Fig. 2. An AVL make Smoke Meter, Model 437 was used for measurement of smoke opacity of exhaust gas. AVL 4000 Di-Gas Analyzer gives emission levels of HC, CO, CO_2, NOx as well as O_2.

Table 2
Engine specifications.

Make	Kirloskar
Model	DAF 8, four stroke diesel engine
Rated brake power (bhp/kW)	8/5.9
Rated speed (rpm)	1500
Number of cylinder	One
Bore × stroke (mm)	95 × 110
Displacement volume (cc)	779.704
Compression ratio	17.5:1
Cooling system	Air cooled
Lubrication system	Forced feed
Cubic capacity	0.78 L
Fuel injection timing (°)	26 BTDC
Injector opening pressure (bar)	200

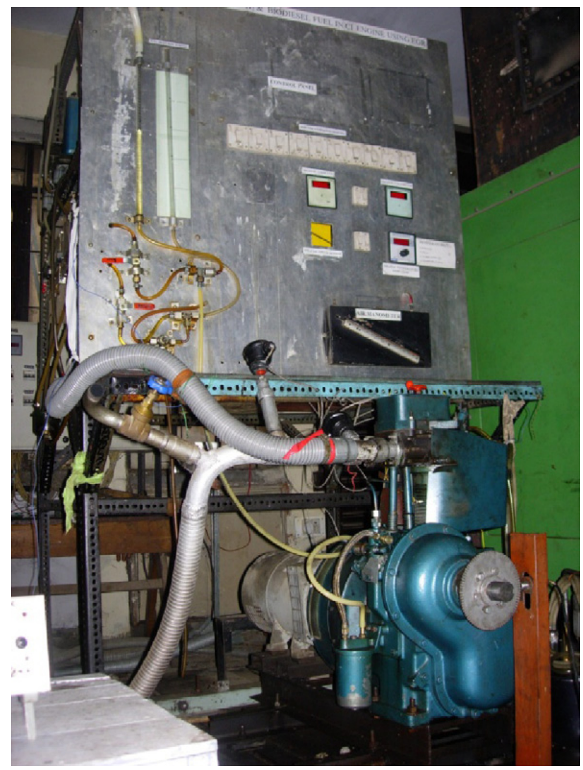

Fig. 1. Test engine.

Fig. 2. AVL 4000 Di-Gas Analyzer and AVL 437 Smoke meter.

3.2.2. Description of tests

Three different types of tests were conducted viz., (i) combustion characteristics, (ii) engine performance and (iii) emission performance. The brief description of these test are mentioned below.

Combustion diagnosis was carried out by means of a Kistler make quartz piezoelectric pressure transducer (Model-701A) fitted on the cylinder head and an electromagnetic pickup (Model-3010AMa) fixed on the output shaft of the engine. The pressure and crank angle signals were fed to a console for onward transmission to a Pentium personal computer through charge amplifier (Model-3059 HICF) and cathode ray oscilloscope (CRO). These instruments were used for measuring the cylinder gas pressure. A two-channel HP 54645A/D oscilloscope digitizing system was used for monitoring different signals such as TDC, crank angle signals for calculation of injection duration and setting the start of injection. It was also used for monitoring cylinder versus pressure crank angle diagram signals from piezoelectric pressure transducer. The pressure transducer was mounted on the cylinder head in the standard position. Piezoelectric pressure transducer has the advantage of good frequency response and linear operating range. A continuous circulation of water was maintained for cooling the transducer by using a small water pump to maintain the required temperature. Distilled water was circulated through the transducer to avoid corrosion of water passage. The charge amplifier and pressure transducer were calibrated by using a dead weight pressure gauge tester. The charge amplifier was used to amplify the output of pressure transducer into the desired voltage level, so that the output of the charge amplifier could be used for recording or display on the oscilloscope screen. Combustion parameters such as peak pressure and heat release rate ignition delay were evaluated. All the tests were conducted by starting the engine with diesel fuel (B0) only. After the engine was warmed up, it was then switched to biodiesel (B100) and their blend (B20). At the end of the test, the fuel was switched back to diesel and the engine was kept running for a while before shut-down to flush out the biodiesel from the fuel line and the injection system.

To evaluate the performance and emission characteristics, experiments were conducted on a commercial DI, air cooled, single cylinder, four stroke, naturally aspirated constant speed compression ignition with prepared test fuels. During the experiments, engine speed, fuel consumption rate, air consumption rate and exhaust gas temperature were recorded to evaluate the performance parameters like brake specific fuel consumption (BSFC), brake mean effective pressure (BMEP) and brake thermal efficiency (BTE) at constant engine speed.

Many studies on the performances and emissions of compression ignition engines, fueled with pure biodiesel made from non edible vegetable oil and blends with diesel fuel have been conducted and are reported in the literature [1–3,5,10,13,14,18,19,29–34]. The details of these feedstock covering different studies as available in literature, are presented in Table 3.

Srivastava and Verma [10] reported that maximum thermal efficiency with karanja biodiesel is about 24.87% whereas that of the diesel is 30.59% at maximum power output. Karanja biodiesel and the blend have higher viscosity and density than the diesel. The higher viscosity leads to decreased atomization, fuel vaporization and combustion, and hence the thermal efficiency of B100 is lower than that of diesel. It is found that the brake thermal efficiency decreases with increase in percentage of unsaturation and density. Many researchers reported that brake thermal efficiency (BTE) obtained for biodiesel blends is slightly higher than diesel. This is due to a reduction in heat loss and increase in power with increase in percent load. Many researchers like Raheman and Phadatare [32], Baiju et al. [34], Sureshkumar et al. [1], Puhan et al. [33], Agarwal and Das [20], Bora and Nath [19], Md. Nabi et al. [29] and Sahoo et al. [18] reported that the smoke, CO and UBHC emissions are reduced in bio-diesel and its blends, because bio-diesel has oxygen in structure and it burns clearly all the fuels. Srivastava and Verma [10], Banapurmath et al. [3] reported that smoke opacity, CO and HC are slightly increased in biodiesel and its blends. Smoke intensity decreases with increase in unsaturation. Baiju et al. [34] and Md. Nabi et al. [29] reported that NOx emissions are slightly increased in bio-diesel and its blends. Increasing density of biodiesel and its blends may increase NO_X. Banapurmath et al. [3] and Rahema and Phadatare [32] reported that NOx emissions are slightly decreased in bio-diesel and its blends. This is due to heat release rates of biodiesels which is lower during premixed combustion phase, leads to lower peak temperatures. Nitrogen oxides formation strongly depends on peak temperature. Many researchers like Rahema and Phadatare [32], Srivastava and Verma [10], and Puhan et al. [33] reported that exhaust gas temperature of bio-diesel and its blends is slightly higher than diesel. This is because of a more unsaturated biodiesel can produce higher value of exhaust gas temperature.

4. Results and discussion

4.1. Fuel characteristics of koroch biodiesel and its comparison with biodiesel produced from similar feedstock

4.1.1. Fatty acid profile of source oil

There have been conclusive evidences of the effect of the characteristics of source oils on the resulted biodiesel. Amongst the oil properties such as density, viscosity, impurity, etc., the fatty acid compositions has a major role in production process as well as quality of biodiesel. Therefore, the fatty acid composition of vegetable oil of koroch seed (koroch oil) is presented in Table 4 and discussed below.

Koroch oil consists of 20.4% saturation comprising of palmitic, stearic and lignoceric acids and 72.4% unsaturation comprising mainly of oleic and linoleic acids (Table 4). As can be seen in Table 4, with reference to saturation vs. unsaturated proportions of fatty acid, korooch seed oil has almost similar compositions as rubber, polonga, karanja and jatropha. However, share of individual components of fatty acid are not uniform amongst the oils considered for the present study. Moreover, saturation percentage in mahua seed oils are the highest (reported in ranges), whereas, cotton seed oil has the lowest share of saturated fatty acid.

Presence of lower fraction of saturated fatty acids like palmitic and stearic gives cloud point below or close to 0 °C. Similarly high concentration of saturated fatty acid exhibits higher cloud point. In terms of saturated fatty acid, koroch can be ranked 4th (Table 4). Koroch and karanja oils are rich in monounsaturated acid (C18:1). In this case, koroch has highest number of monounsaturation (Table 4). The presence of monounsaturated acid gives a high cetane number to koroch and karanja biodiesels. In comparison to koroch oil, cotton seed oil is richer in unsaturated ester of linoleic acid (C18:2). Monounsaturated fatty acid such as oleic acid is considered to be better than polyunsaturated ones such as linoleic and linolenic acid (C18:3) for cetane number. Biodiesel which exhibits higher unsaturated ester of linoleic acid generally presents a cetane number in the medium range.

It is reported that composition of fatty acids contained in vegetable oil depends on the plant species and also on the growth conditions of the plant. Thus, the variations of fatty acids compositions amongst these seven plant oils might be attributed to such variations [38]. Further, it is reported that saturated fatty acid methyl esters increase the cloud point, cetane number and improve stability whereas more polyunsaturates reduce the cloud point, cetane number and stability [37].

Table 3
Description of engine tests concerning some biodiesel research.

Sl no.	Type of engine used	Fuel used	Region of investigation, year of investigation	Test conditions blends and load	Researchers	Remarks
1a	Single cylinder, four-stroke, DI, water-cooled diesel engine having a rated output of 7:5 kW at 3000 rpm and a compression ratio of 16:1	Karanja oil methyl ester (B100) and its blends (B20, B40, B60 and B80)	Kharagpur, India 2004	BTE obtained for B20 and B40 were higher CO, smoke, NOx emissions were lower exhaust temperature slightly higher	Raheman and Phadatare [32]	Blends of karanja methyl ester with diesel up to 40% by volume could replace diesel for running diesel engine
1b	Single cylinder four stroke naturally aspirated DI diesel engine having rated power 5.9 kW at 1500 rpm and a compression ratio of 17.5:1	Karanja oil methyl ester (B100 KOME), karanja oil ethyl ester(B100KOEE) and its blends (B20, B40, B60 and B80)	Delhi, India 2009	BTE obtained for B100 was almost same smoke, CO, NOx emissions were lower for B100	Baiju et al. [34]	In view of the petroleum fuel shortage, biodiesel can certainly be considered as a potential candidate
1c	Twin cylinder vertical high speed Petter Kirloskar diesel engine having rated power 10 hp and compression ratio 16.5:1	Methyl ester of karanja oil and its blends	Jharkhand, India 2008	BTE is lower for karanja biodiesel exhaust gas temperature is higher for karanja biodiesel HC, CO, NO are higher for biodiesel at maximum load	Srivastava and Verma [10]	Methyl ester of karanja oil can be used as an alternative renewable source of energy
2	Single cylinder four-stroke, water-cooled and constant-speed (1500 rpm) compression ignition engine having brake power 3.68 kW and compression ratio 16.5:1	Pongamia pinnata methyl ester (PPME) and its blends	Tamil Nadu, India 2008	BSFC of b20 is lower PPME emits less HC, CO NOx emission reduces with increase of PPME concentration Exhaust temperature decreases for PPME	Sureshkumar et al. [1]	Blends of PPME with diesel up to 40% by volume (B40) could replace the diesel for diesel engine applications for getting less emissions and better performance
3	Four-stroke single cylinder direct-injection CI engine having rated power 5.2 kW at 1500 rpm	Jatropha oil methyl esters (JOME)	Hubli, India 2008	BTE was lower for JOME at 80% load smoke, HC, CO emissions were higher and NOx was lower for JOME	Banapurmath et al. [3]	It was operated on JOME at optimum injection timing (27 °C) and injection pressure (220 bar)
4	Kirloskar, single cylinder, four stroke constant speed, vertical, water cooled, direct injection having rated output 3.7 kW at 1500 rpm, compression ratio 16.5:1	Mahua oil methyl ester (MOME)		BSFC and exhaust gas temperature are higher for MOME is higher smoke, CO are lower for MOME	Puhan et al. [33]	A slight power loss, combined with an increase in fuel consumption, was experienced with MOME
5	A single cylinder, direct injection, water cooled, portable diesel engine having rated power 4 kW at 1500 rpm, compression ratio 16.7:1	Linseed oil methyl ester (LOME) and its blends	Delhi, India 2001	BTE increases by increasing concentration of biodiesel in the blend smoke is lower for biodiesel blend exhaust temperature increases for blend B20 gave 5% higher NOx emissions	Agarwal and Das [20]	Biodiesel blend with concentration of 20% gave maximum improvement in peak thermal efficiency
6	A 5 hp,1500 rpm, single cylinder, direct injection, water-cooled, portable diesel engine	Nahor oil methyl ester (NOME) and its blends (B10, B20, and B30)	Assam, India 2007	Improvement of BTE with blends smoke opacity for biodiesel blends is lower	Bora and Nath [30]	B30 can be effectively used in unmodified existing diesel engine
7	A single cylinder water-cooled, NA, DI diesel engine having rated output 9.8 kW at 2000 rpm, compression ratio 20:1	Biodiesel from non-edible neem oil (NOME)	Bangladesh 2006	With an increase in engine speed up to 1000 rpm, the BTE of the engine increases. CO, smoke decreases for blends NOx increases	Md. Nabi N et al. [29]	Injection timing 13CATDC is optimum for minimum NOx emission
8	A small-size water-cooled direct injection diesel engine (engine power is not mentioned)	Polanga oil based mono esters (POME) and its blends	Delhi, India 2007	BTE of B100 improves slightly specially at lower loads smoke, NOx are significantly reduced	Sahoo et al. [18]	From emission point of view the neat POME was found to be the best fuel as it showed lesser exhaust emission as compared to diesel
9	Four-stroke single cylinder direct-injection CI engine having rated power 5.2 kW at 1500 rpm, compression ratio 17.5:1	Honge oil methyl esters (HOME)	Hubli, India 2008	BTE for HOME was lower At 80% load smoke opacity, HC, CO, NOx were higher	Banapurmath et al. [3]	On the whole it is seen that operation of engine is smooth on HOME It was operated on HOME at optimum injection timing (19 °C) and injection pressure (205 bar)

Table 4
Fatty acid composition of koroch oil and its comparison with similar feedstock.

Fatty acid	Koroch seed oil (%)	Rubber seed oil (%)	Mahua seed oil (%)	Polanga seed oil (%)	Cotton seed oil (%)	Karanja seed oil (%)	Jatropha seed oil (%)
Palmitic (C16:0)	7.9	10.2	16.0–28.2	12.01	11.67	11.65	16.0
Stearic (C18:0)	8.9	8.7	20.0–25.1	12.95	0.89	7.50	6.5
Lignoceric (C20:0)	3.5	–	–	–	–	–	–
Arachidic (C20:1)	–	–	0.0–3.3	–	–	–	–
Oleic (C18:1)	57.9	24.6	41.0–51.0	34.09	13.27	51.59	43.5
Linoleic (C18:2)	14.5	39.4	8.9–13.7	38.26	57.51	16.46	34.4
Linolenic acid (C18:3)	–	16.3	–	0.3	–	2.65	0.8
Total saturated	20.4	18.9	36–53.3	24.96	12.56	19.15	21.5
Total unsaturated	72.4	80.5	49.9–68.0	72.65	70.88	70.70	78.7

Table 5
Properties of koroch biodiesel in comparison with other biodiesels.

Properties	Koroch	Polanga	Mahua	Rubber	Karanja	Jatropha
Viscosity at 40 °C (cSt)	4.08	4.92 [18]	3.98 [7]	5.81 [9]	3.99 [34]	4.40 [35]
Density at 15 °C (kg/m^3)	870	–	880 [7]	874 [9]	880 [34]	880 [8]
Calorific value (MJ/kg)	35.72	38.66 [18]	37 [7]	36.50 [9]	36.12 [32]	39.23 [8]
Acid value (mg KOH/g)	0.23	–	0.41 [7]	0.12 [9]	0.43 [34]	0.40 [8]
Flash point (°C)	145	140 [18]	208 [7]	130 [9]	160 [34]	163 [35]
Copper strip corrosion at 100 °C, for 3 h	1a	–	–	–	–	1 [35]
Sulfated ash, max (%mass)	0.004	–	0.01 [7]	–	0.001 [34]	0.002 [35]
Moisture content, max (mg/kg)	0.005	–	0.04 [7]	–	0.03 [34]	0.025 [8]
Cetane number	53.40	–	51 [36]	–	57.60 [34]	57.1 [35]
Ester content (%mass)	>97	–	98 [7]	–	>98 [34]	>99 [8]
Cloud point (°C)	4	13.2 [18]	5 [36]	4 [9]	12 [34]	4 [35]
Pour point (°C)	1	4.3 [18]	6 [7]	−8 [9]	5 [34]	2 [8]

4.1.2. Characteristics of koroch biodiesel and its comparison with biodiesel obtained from similar feedstock

In general, biodiesel is characterized by its viscosity, calorific value, density, cetane number, cloud and pour points, distillation range, flash point, ash content, sulfur content, carbon residue, acid value and copper corrosion. The characteristics of koroch biodiesel obtained in the present investigation in terms of these parameters are presented in Table 5, along with the results reported for similar biodiesel (5 different types of biodiesel) by earlier investigators. The results pertaining to viscosity, cetane number, calorific value and cloud point are discussed below.

Table 5 shows some fuel properties of six methyl ester biodiesels including koroch biodiesel given by different researchers.

4.1.2.1. Viscosity. One major objective of the transesterification process is to reduce the viscosity which is found to attain by all the results considered for the present study. The reported results of viscosity of five biodiesel (with varying feedstock) are compared with the viscosity of koroch biodiesel of the present investigation. Koroch biodiesel with 4.08 cSt (84% of reduction of viscosity over vegetable oil), ranks 3rd amongst the biodiesel types considered for the present study (Table 6). Higher viscosity of koroch biodiesel than mahua biodiesel could be explained by the presence of lignoceric acid (C20:0). It is known fact that viscosity increases with chain length and with increasing degree of saturation. However, the karanja biodiesel in spite of possessing about 2.65% linolenic acid in its source oil (which is absent in koroch), exhibited marginally lower viscosity than koroch. This might be due to differences in processing, as two step transesterification was followed for preparing karanja biodiesel and percentage of saturation in case of koroch (20.4%) is higher than karanja (19.15%) [36]. Similarly, the highest viscosity (5.81 cSt) exhibited by rubber seed oil might be due to presence of higher percentage of linolenic acid (16.3%).

Table 6
Ranking of biodiesel in terms of viscosity.

Biodiesel	Viscosity (cSt)	Rank
Mahua	3.98	1st
Karanja	3.99	2nd
Koroch	4.08	3rd
Jatropha	4.4	4th
Polanga	4.92	5th
Rubber	5.81	6th

4.1.2.2. Cetane number. The properties of the triglyceride and the biodiesel fuel are determined by the amounts of each fatty acid that are present in the molecules. Chain length and number of double bonds determine the physical characteristics of both fatty acids and triglycerides [36]. Transesterification does not alter the fatty acid composition of the feedstocks and this composition plays an important role in some critical parameters of the biodiesel, as cetane number and cold flow properties.

It is well known that biodiesel cetane number depends on the feedstock used for its production. The longer the fatty acid carbon chains and the more saturated the molecules, the higher the cetane number. Koroch biodiesel with 53.40 ranks 3rd amongst the biodiesel types considered for the present study (Table 6). Though total saturated fatty acids are more in case of koroch oil (20.4%) than karanja oil (19.15%) but due to the higher percentage of palmitic acid (11.65%) present in karanja oil may increase the cetane number. High cetane numbers are observed for esters of saturated fatty acids such as palmitic (C16:0) and stearic (C18:0) acids [37]. Since cetane number depends on feedstock, may be that reason cetane number is higher in for karanja biodiesel. Jatropha biodiesel is ranked 2nd amongst these biodiesel because of higher percentage of saturated acid available in jatropha oil (21.5%) (Table 7).

4.1.2.3. Calorific value. Calorific value is another fuel property indicating the suitability of fatty compounds as diesel fuel. Calorific value increases with chain length (number of carbons and hydrogens in biodiesel molecules) and decreases with an increasing unsaturation. The calorific value or calorific content is the energy content of the oil. Fuels with more unsaturation generally have lower energy (on a weight basis) while fuels with greater saturation

Table 7
Ranking of biodiesel in terms of cetane number.

Biodiesel	Cetane number	Rank
Karanja	57.6	1st
Jatropha	57.1	2nd
Koroch	53.40	3rd
Mahua	51	4th
Polanga	n.a.	–
Rubber	n.a.	–

Table 8
Ranking of biodiesel in terms of calorific values.

Biodiesel	Calorific value	Rank
Jatropha	39.23	1st
Polanga	38.66	2nd
Mahua	37.00	3rd
Rubber	36.50	4th
Karanja	36.12	5th
Koroch	35.72	6th

have higher energy content. Denser fuels provide greater energy per gallon and since fuel is sold volumetrically, the higher the density greater the potential energy [38]. Calorific value obtained for jatropha biodiesel (39.23 MJ/kg) is highest amongst these biodiesels and lowest for koroch biodiesel (35.72 MJ/kg). This may be due to the lower density of koroch biodiesel (870 kg/m^3). Other biodiesels such as jatropha (880 kg/m^3), mahua (880 kg/m^3), rubber (874 kg/m^3), and karanja (880 kg/m^3) have higher densities than koroch (Table 5). Biodiesels are shown in Table 8 according to their rank with respect to calorific values.

4.1.2.4. Cloud point. Studies about the influence of the triglycerides composition in the biodiesel quality are scarce. Saturated fatty compounds have significantly higher melting points than unsaturated fatty compounds and in a mixture they crystallize at higher temperature than the unsaturated. Thus biodiesel fuels derived from fats or oils with high concentration of saturated fatty compounds will display higher cloud points and pour points. Trace of monoglycerides alone in biodiesel (0.6% or higher), may increase in cloud point. In addition, soaps or water in combination with monoglycerides would also increase the cloud point. So production process is also very important for a particular biodiesel from their feedstock. Cloud point of koroch, polanga, mahua, rubber, karanja and jatropha biodiesels are 4, 13.2, 5, 4, 12 and 4 °C. Though mahua biodiesel has higher saturated fatty acid compounds (36.0–53.3%), its cloud point is found 5 °C. This may be due to production process of biodiesel. Though the saturated fatty acid is 19.5% for karanja biodiesel, its cloud point obtained is 12 °C. This may be due to water or glyceride availability of in the biodiesel. In a research paper cloud point of karanja biodiesel is given as −2 though fatty acid profile is not presented in the paper [10]. This is because of lower saturated fatty acid profile of karanja oil. Since saturated fatty acid is 24.96% for polonga biodiesel, its cloud point obtained is 13.2 °C. Biodiesels are shown in Table 9 according to their rank with respect to cloud point.

Table 9
Ranking of biodiesel in terms of cloud point.

Biodiesel	Cloud point (°C)	Rank
Koroch	4	1st
Jatropha	4	1st
Rubber	4	1st
Mahua	5	2nd
Karanja	12	3rd
Polanga	13.2	4th

4.2. Performances of engine fueled by koroch biodiesel and their comparison with similar engine test results

4.2.1. Power performance

The performance of the engine was evaluated in terms of brake thermal efficiency and exhaust temperature to compare the various blends of koroch biodiesel and diesel with diesel.

Biodiesel having more unsaturated fatty acids and density exhibit lower thermal efficiency compared to biodiesel having more saturated acids. From Table 4, it is seen that all biodiesels such as koroch (70.4%, 870 kg/m^3), rubber seed (80.5%, 874 kg/m^3), polanga (72.65%, n.a.), cotton seed (70.88%, n.a.), karanja (70.70%, 880 kg/m^3) and jatropha (78.7%, 880 kg/m^3) have more unsaturated acids except mahua biodiesel (49.9–68.0%, 880 kg/m^3). The maximum brake thermal efficiencies (BTE) were obtained to be 26.79 and 26.19 for B20 and B40 of karanja biodiesel, respectively, which were higher than that of diesel (24.62%) [32]. Blend of koroch esterified oil (B20) gives slightly higher BTE than diesel. This may be due to higher calorific value of karanja biodiesel (36.12 MJ/kg) than koroch biodiesel (35.72 MJ/kg). The maximum BTE were 25 and 24 for B20 and B40 of mahua biodiesel, respectively, as compared to 24% for diesel [39]. Though mahua biodiesel has a higher percentage of saturation compared to other biodiesel still it shows lower thermal efficiency in case of B60, B80 and B100. This may be due to the contribution of stearic acid (20.0–25.1%) which is relatively higher in mahua biodiesel than that of other biodiesel. The trends of the brake thermal efficiency for polonga biodiesel (B100) and its blends show lower BTE than neat petroleum based diesel fuel [18]. This may be due to higher percentage of unsaturation of polonga biodiesel. The maximum brake thermal efficiency obtained is about 28% for B10 of rubber seed biodiesel, which is quite higher than that of diesel (25%). The maximum brake thermal efficiency obtained while using B50, B75 and B100 (rubber seed biodiesel) are, respectively, 25, 25 and 24% [40]. The possible reason for this is the additional lubricity provided by the rubber biodiesel.

Fig. 3 represents the brake thermal efficiency (BTE) of the engine fueled with diesel and different diesel–koroch biodiesel fuel blends. The above figure indicates lower thermal efficiency particularly at higher loads with biodiesel blends.

More unsaturated biodiesel can produce higher value of exhaust gas temperature as compared to a less unsaturated one. This is believed due to the more afterburning stage for higher unsaturated biodiesel fuels which may increase the exhaust gas temperature. The exhaust temperature was varied from 186 °C to 556 °C for koroch biodiesel blends as compared to 184 °C to 543 °C for diesel. Koroch oil also consists of 72.4% unsaturation comprising mainly of oleic and linoleic acids. For B20–B100 of karanja biodiesel, the exhaust temperature measured varied between 260 °C and 336 °C as compared to 262 °C and 335 °C for diesel indicating no much variation in exhaust temperature [32]. This may be due to high unsaturated acids (70.70%) of karanja oil. Since the unsaturated

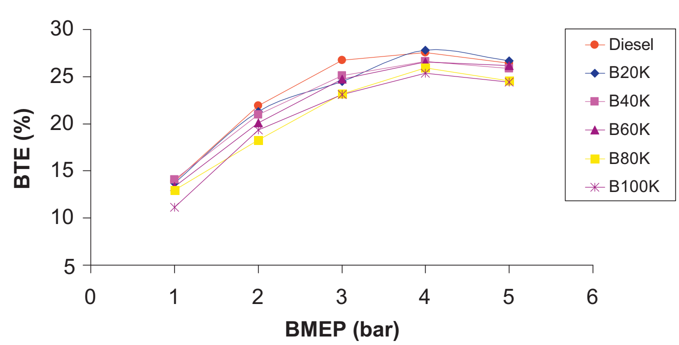

Fig. 3. Variation of BTE with BMEP.

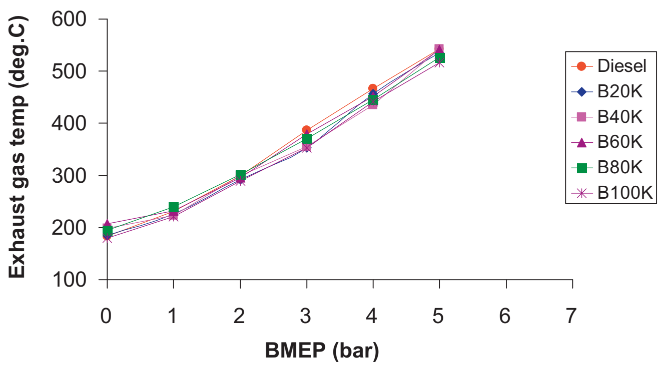

Fig. 4. Variation of exhaust gas temperature with BMEP.

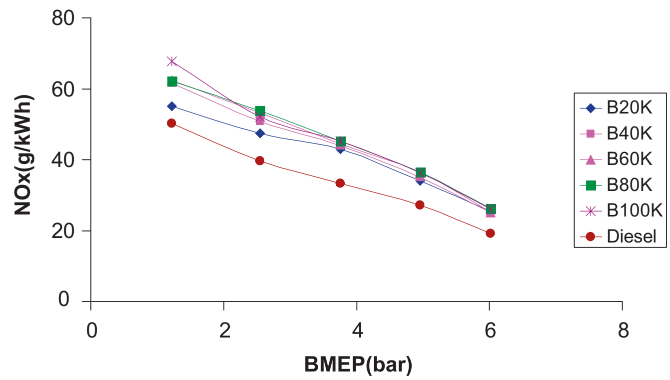

Fig. 6. Variation of NOx emissions with BMEP.

fatty acid percentage is lower in case of karanja oil, so the range of exhaust gas temperature is short. The mean exhaust gas temperature (EGT) increased linearly from 171 °C at no load to 285 °C at full load conditions with an average increase of 15% with every 25% increase in load for mahua biodiesel. The mean EGTs of B20, B40, B60, B80 and B100 were 6%, 10%, 12%, 14% and 16% higher than the mean EGT of HSD, respectively [39]. More saturated mahua biodiesel can produce lower value of exhaust gas temperature. For MOME (B100) the exhaust gas temperature is higher compared to diesel fuel. This may be due to longer after burning stage [33]. Exhaust gas temperature is lower for B10 and B20 rubber biodiesel in comparison to diesel. Exhaust gas temperature is higher for B50, B75 and B100 of rubber seed biodiesel in comparison to diesel. This is due to higher unsaturation (80.5%) of rubber seed oil.

The variation of exhaust temperature with load for different fuels tested is compared with diesel in Fig. 4. The new generation vehicle is optimized for meeting emission norms and therefore the emission test is essential for recommending the best fuel. The results of the emission levels for CO, NOx, smoke and HC emissions for koroch biodiesel and their blends are shown in Figs. 5–8.

Fig. 5 shows the variation of smoke opacity with BMEP. Smoke is emitted as a product of the incomplete combustion process, particularly at maximum loads. Smoke particles are formed from the fuel deposited on walls or in the spray core, especially under elevated loads. It was seen that the smoke intensity for biodiesel fuels decreases with increase in percentage of unsaturation. It must be noted that the unsaturation is nothing but the deficiency of hydrogen atoms. Greater unsaturation represents the greater deficit of hydrogen atoms. Therefore, for a given supply of air (and oxygen) to the engine, if unsaturation is more, carbon molecules could find more oxygen molecules to react with due to the less number of hydrogen molecules. Therefore, the biodiesel with more unsaturation can have a higher degree of oxidation process than that of the biodiesel with less unsaturation. Hence, it can be stated that the smoke intensity decreases with increase in unsaturation.

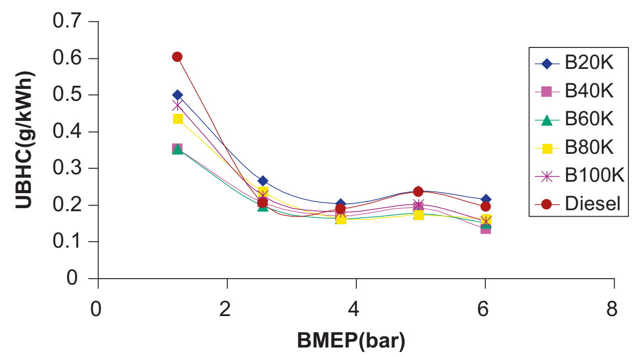

Fig. 7. Variation of unburnt hydrocarbon emission with BMEP.

The minimum and maximum smoke densities produced for B20–B100 of karanja biodiesel were 1% and 3% with a maximum and minimum reduction of 80% and 20%, respectively, as compared to diesel. This may be due to high unsaturated fatty acids available in karanja oil. Smoke opacity decreases up to 19.7% on different diesel–koroch biodiesel fuel blends at different loading conditions in comparison to mineral diesel fuel. It was seen that around 11% reduction in smoke number produced in mahua biodiesel compared with diesel. Mahua oil also contains 49.9–68.0% unsaturated acids. The smoke is significantly reduced for polanga biodiesel of higher blends (B60 and B100) as compared to neat petroleum based diesel fuel. This may be due to high unsaturated fatty acids available in polanga oil. Smoke density for rubber seed biodiesel blend is noticed to be generally lower than that of the diesel oil. B20 blends gave smoke density of 28% as compared to 45% in the case of diesel. This may be due to high unsaturated fatty acids (80.5%) available in rubber seed oil.

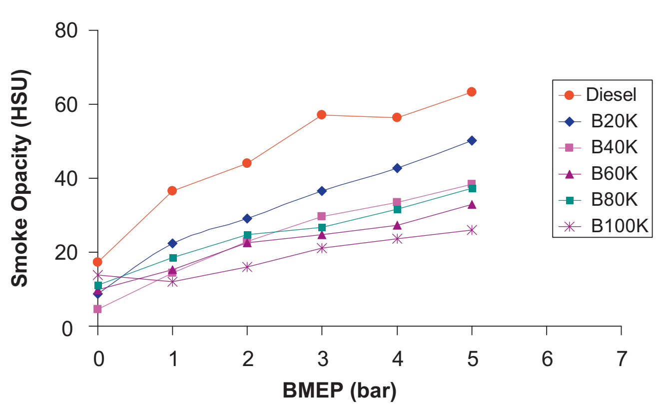

Fig. 5. Variation of smoke opacity with BMEP.

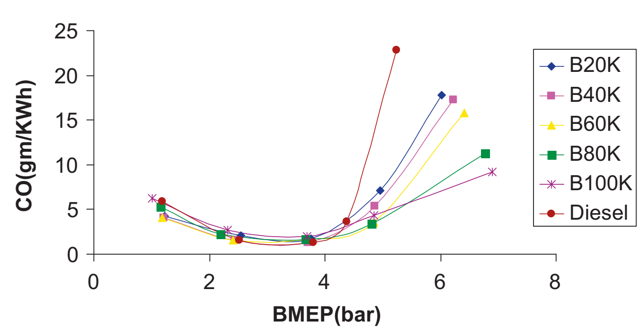

Fig. 8. Variation of carbon monoxide emission with BMEP.

The NOx emissions of diesel engine fueled with diesel–biodiesel blends and diesel fuel at selected operating conditions are shown in Fig. 6. The emissions of the blends increases up to 21.88% with increasing biodiesel content at the same load but rate of NOx emissions decreases with increasing brake load for all diesel–koroch biodiesel fuel blends.

NOx concentration in the exhaust emissions increases with increase in biodiesel density and percentage of unsaturation. Increasing density may increase NOx because the fuel injector injects a constant volume, but larger mass, of the more dense fuels. Since a larger mass of the fuel is burned more NOx is produced.

The amount of NOx produced for B20–B100 varied between 4 and 12 ppm as compared to 12 and 13 ppm for diesel. On an average a 26% reduction in NOx was obtained for karanja biodiesel and its blends as compared to diesel. In comparison to other vegetable oil except mahua, karanja oil has lower unsaturated fatty acids so NOx is reduced (Table 4). The amount of NOx produced for B20–B100 varied between 17 and 50 ppm as compared to 17–44 ppm for diesel. NOx emissions slightly increase (within 6%) when compared with that of pure diesel. This may be due to the lower percent of unsaturation of mahua biodiesel. It is seen that the NOx emissions in the case of polonga biodiesels are lower by approximately 4%. This may be because of engine geometry, compression ratio, less reaction time and temperature in case of biodiesel. The emissions of the NOx increases up to 21.88% with increasing koroch biodiesel content at the same load. This may be due to high percentage of unsaturated fatty acids available in koroch oil.

The unburnt hydrocarbon emission trends for diesel–koroch biodiesel fuel blends and neat diesel fuel are shown in Fig. 7. It is very clear from the figure that koroch biodiesel and biodiesel blends emit lower UBHC. UBHC emission decreases 25–35% at higher load for all diesel–koroch biodiesel fuel blends.

Unburnt hydrocarbon (UBHC) and carbon monoxide (CO) emission levels in diesel engines are small in absolute terms, so that they are of no real concern. But still if fairly reasonable to discuss the effect of biodiesel properties and fatty acid composition on CO and HC emissions. UBHC emission increases with increase in unsaturation. This may be believed due to the lower oxygen concentration in higher unsaturated biodiesel fuels. The oxygen content decreases with increase in unsaturation.

The UBHC emission of karanja biodiesel is 120 ppm. This may be due to increase in unsaturation. However, emission is lower with the blend as compared to biodiesel. This may be due to physical property of the fuel such as viscosity that affects the penetration rate, maximum penetration and droplet size which in turn affects the mixing of fuel and air. It is seen from literature that a reduction of nearly 35% in UBHC emission in case of mahua biodiesel compared to diesel is obtained. This may be due to higher saturation of mahua biodiesel. Neat polonga biodiesel (B100) gives relatively lower HC as compared to the neat diesel. Biodiesel of polonga has a higher percentage of unsaturation, but still has a lower value of UBHC. Nevertheless this odd relationship cannot be justified very precisely. UBHC emission decreases 25–35% at higher load for all diesel–koroch biodiesel fuel blends. This may be due to lower density of the biodiesel.

Carbon monoxide (CO) emissions were low in case of diesel–koroch biodiesel fuel blends. Reduction of CO emission varied from 41.9 to 50.9% at higher load for all diesel–koroch biodiesel fuel blends. The presence of oxygen in the fuel, which helps to promote combustion processes, in turn reduces the exhaust emissions compared to diesel (Fig. 8).

CO emission increases with increase in unsaturation. This may be believed due to the lower oxygen concentration in higher unsaturated biodiesel fuels. The oxygen content decreases with increase in unsaturation. Carbon monoxide is believed to be formed at the borders between the lean flame out region (LFOR) and lean flame region (LFR) during the early stages of spray combustion. At this stage, primary reaction can take place and the initial hydrocarbons may reduce to CO, H_2, and H_2O. As the local temperature is not enough at this stage, very little oxidation reactions take place. Increase in unsaturation may tend to decrease the gas temperature. The reduced gas temperature may not provide a positive situation for complete oxidation reaction thereby increase the CO concentration.

Carbon monoxide is formed whenever carbon or substances containing carbon are burned with an insufficient air supply. Even though the amount of air required for combustion is theoretically sufficient, the reaction is not always complete. The combustion gases still contain some free oxygen and carbon monoxide. Biodiesel also contains free oxygen in its structure and percentage of oxygen increases with the percentage of biodiesel blend. Carbon monoxide (CO) emissions tend to decrease because of the oxygen content and the enhanced cetane number of biodiesel fuel which helps for a more complete combustion.

The minimum and maximum CO produced in case of karanja biodiesel and their blends were 0.004, 0.016% resulting in a reduction of 94% and 73%, respectively, as compared to diesel. This may be due to higher cetane number (57.60) present in karanja biodiesel which helps in complete combustion of the biodiesel. Carbon monoxide emissions were extremely low in the case of mahua biodiesel. The minimum and maximum CO produced were 0.02–0.2% resulting in a reduction of 81 and 12%, respectively, as compared to diesel. This may be due to high saturated acids present in the biodiesel. Green house emission like carbon dioxide emission has shown 40% of reduction for B20 and B100 of polonga biodiesel as compared to neat diesel fuel. Present theory available is not support this result. Reduction of CO emission varied from 41.9 to 50.9% at higher load for all diesel–koroch biodiesel fuel blends. This may be the higher cetane number (53.40) available which helps in complete combustion. CO emission level decreases with increasing rubber seed biodiesel percentage in the fuel. Carbon monoxide (CO) emissions tend to decrease because of biodiesel contains free oxygen in its structure and the enhanced cetane number of biodiesel fuel which helps for a more complete combustion.

A higher density fuel may expect to have a lower value of maximum heat release rate. Again, calorific value decreases with increase in unsaturation. Hence, for given value of mass fraction burnt, the fuel with lower heating value may release lesser heat energy as compared to the fuel with higher calorific value. Increase in peak pressure value of biodiesel is believed to be higher value of maximum heat release rate and lower percentage of unsaturation, respectively.

The in-cylinder pressures of the diesel engine fueled with diesel–biodiesel fuel at the same operating condition. Peak pressure

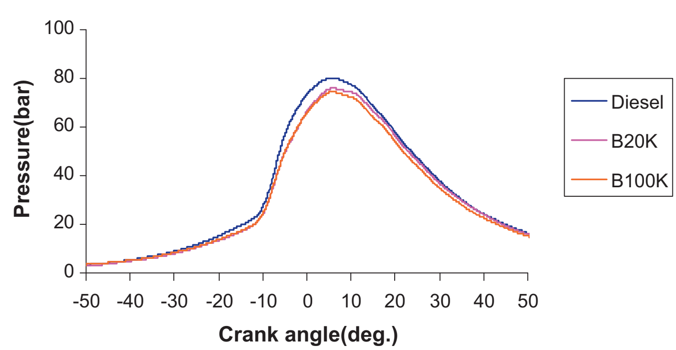

Fig. 9. Pressure crank angle diagram for diesel–biodiesel (KOME) fuel blends.

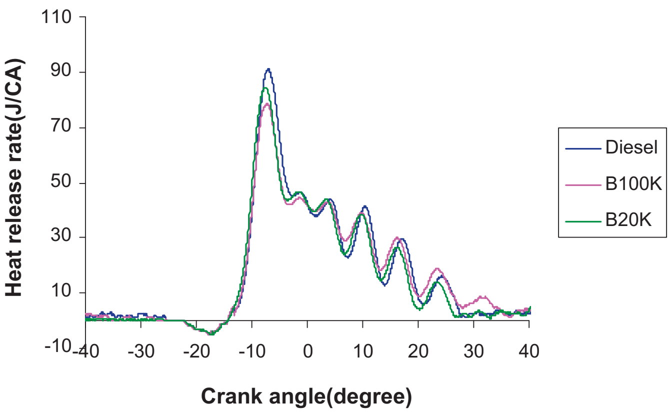

Fig. 10. Heat release rate for diesel–biodiesel (KOME) fuel blends.

mainly depends on the combustion rate in the initial stages, which is influenced by the fuel taking part in uncontrolled heat release phase. The high viscosity and low volatility of the diesel–koroch biodiesel blend leads to poor atomization and mixture preparation with air. The cylinder peak pressure was found lowest for B100 (Fig. 9). The heat release rate at selected operating points of different diesel–koroch biodiesel blend fuels and neat diesel fuel are shown in Fig. 10. Engine performance parameters using different biodiesel in different engine are presented in Table 3.

5. Conclusion

There have been extensive search for biodiesel feedstock all over the World. In this connection, oils of non-edible tree seeds are also getting adequate research attention. Status of research works concerning biodiesel from non-edible tree-based oil seeds are reviewed and found to follow certain distinct processes of transesterification based on the nature of fatty acid compositions of feedstock. Variations of biodiesel quality are prominent amongst the types of biodiesel considered for the study. No biodiesel types are found to qualify all the quality norms as per stated standards (ASTM D 6751 or EN 14214). Optimal blending of different types of biodiesel targeting improvement of individual quality parameters would be possible. Quality of biodiesel from seed oil of koroch tree, which is a forest tree available in Assam (India), is comparable with biodiesel of similar feedstocks. Except calorific value, other quality parameters of koroch biodiesel are better than some of the biodiesel types reported in literature. Engine performance results are also reviewed and found to have a varied test conditions with reference to engine size, blending level and loading pattern. However, general consensus on the effect of fatty acid composition on brake thermal efficiency is observed with lowering thermal efficiency by the presence of higher percentage of unsaturated fatty acids.

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References

[1] Sureshkumar K, Velraj R, Ganesan R. Performance and exhaust emission characteristics of a CI engine fueled with Pongamia pinnata methyl ester (PPME) and its blends with diesel. Renewable Energy 2008;33:2294–302.
[2] Raheman H, Ghadge SV. Performance of diesel engine with biodiesel at varying compression ratio and ignition timing. Fuel 2008;87:2659–66.
[3] Banapurmath NR, Tewari PG, Hosmath RS. Performance and emission characteristics of a DI compression ignition engine operated on Honge, Jatropha and sesame oil methyl esters. Renewable Energy 2008;33:1982–8.
[4] Sharma YC, Singh B. Development of biodiesel from karanja, a tree found in rural India. Fuel 2008;87:1740–2.
[5] Mahanta P, Sarmah JK, Kalita P, Shrivastava A. Parametric study on transesterification process for biodiesel production from *Pongamia pinnata* and *Jatropha curcus* oil. International Energy Journal 2008;9(1).
[6] Chongkhong S, Tongurai C, Chetpattananondh P, Bunyakan C. Biodiesel production by esterification of palm fatty acid distillate. Biomass and Bioenergy 2007;31:563–8.
[7] Vilas Ghadge S, Raheman H. Biodiesel production from mahua (*Madhuca indica*) oil having high free fatty acids. Biomass and Bioenergy 2005;28: 601–5.
[8] Tiwari AK, Kumar A, Raheman H. Biodiesel production from jatropha oil (*Jatropha curcas*) with high free fatty acids: an optimized process. Biomass and Bioenergy 2007;31:569–75.
[9] Ramadhas AS, Jayaraj S, Muraleedharan C. Biodiesel production from high FFA rubber seed oil. Fuel 2005;84:335–40.
[10] Srivastava PK, Verma M. Methyl ester of karanja oil as an alternative renewable source energy. Fuel 2008;87:1673–7.
[11] Patil PD, Deng S. Optimization of biodiesel production from edible and non-edible vegetable oils. Fuel 2009;88:1302–6.
[12] Ghadge SV, Raheman H. Process optimization for biodiesel production from mahua (*Madhuca indica*) oil using response surface methodology. Bioresource Technology 2006;97:379–84.
[13] Panwar NL, Shrirame HY, Rathore NS, Jindal S, Kurchania AK. Performance evaluation of a diesel engine fueled with methyl ester of castor seed oil. Applied Thermal Engineering 2010;30:245–9.
[14] Agarwal AK, Das LM. Biodiesel development and characterization for use as a fuel in compression ignition engines. Transactions of the ASME 2001;123:440–7.
[15] Meher LC, Vidya Dharmagadda SS, Naik SN. Optimization of alkali-catalyzed transesterification of *Pongamia pinnata* oil for production of biodiesel. Bioresource Technology 2006;97:1392–7.
[16] Karmee SK, Chadha A. Preparation of biodiesel from crude oil of *Pongamia pinnata*. Bioresource Technology 2005;96:1425–9.
[17] Naik M, Meher LC, Naik SN, Das LM. Production of biodiesel from high free fatty acid Karanja (*Pongamia pinnata*) oil. Biomass and Bioenergy 2008;32: 354–7.
[18] Sahoo PK, Das LM, Babu MKG, Naik SN. Biodiesel development from high acid value polanga seed oil and performance evaluation in a CI engine. Fuel 2007;86:448–54.
[19] Bora DK, Nath R. Use of nahar oil methyl ester (NOME) in C.I. engines. Journal of Scientific & Industrial Research March 2007;66:256–8.
[20] Agarwal AK, Das LM. Biodiesel development and characterization for use as a fuel in compression ignition engine. Journal of Engineering for Gas Turbine and Power (ASME Transactions) 2001;123(April (2)):440–7.
[21] Sarma AK, Konwer D, Bordoloi PK. A comprehensive analysis of fuel properties of biodiesel from koroch seed oil. Energy & Fuels 2005;19:656–7.
[22] Bajpai D, Tyagi VK. Biodiesel: source, production, composition, properties and its benefits. Journal of Oleo Science 2006;55(10):487–502.
[23] May CY, Lianga YC, Foona CS, Ngana MA, Hookb CC, Basirona Y. Key fuel properties of palm oil alkyl esters. Fuel 2005;84:1717–20.
[24] Shang Q, Jiang W, Lu H, Liang B. Properties of tung oil biodiesel and its blends with 0 diesel. Bioresource Technology 2010;101:826–8.
[25] Moser BR, Vaughn SF. Evaluation of alkyl esters from *Camelina sativa* oil as biodiesel and as blend components in ultra low-sulfur diesel fuel. Bioresource Technology 2010;101:646–53.
[26] Lu H, Liu Y, Zhou H, Yang Y, Chen M, Liang B. Production of biodiesel from *Jatropha curcas* L. oil. Computers and Chemical Engineering 2009;33: 1091–6.
[27] Canoira L, Alcántara R, García-Martínez MJ, Carrasco J. Biodiesel from Jojoba oil-wax: transesterification with methanol and properties as a fuel. Biomass and Bioenergy 2006;30:76–81.
[28] Eevera T, Rajendran K, Saradha S. Biodiesel production process optimization and characterization to assess the suitability of the product for varied environmental conditions. Renewable Energy 2009;34:762–5.
[29] Md. Nabi N, Md. Akhter S, Mhia Md. Shahadat Z. Improvement of engine emissions with conventional diesel fuel and diesel–biodiesel blends. Bioresource Technology 2006;97:372–8.
[30] Basha SA, Raja Gopal K, Jebaraj S. A review on biodiesel production, combustion, emissions and performance. Renewable and Sustainable Energy Reviews 2009;13:1628–34.
[31] Murugesan A, Umarani C, Subramanian R, Nedunchezhian N. Bio-diesel as an alternative fuel for diesel engines—a review. Renewable and Sustainable Energy Reviews 2009;13:653–62.
[32] Raheman H, Phadatare AG. Diesel engine emissions and performance from blends of karanja methyl ester and diesel. Biomass and Bioenergy 2004;27:393–7.
[33] Puhan S, Vedaraman N, Bharat Ram BV, Sankaranarayanan G, Jeychandran K. Mahua oil (Madhuca Indica seed oil) methyl ester as biodiesel-preparation and emission characteristics. Biomass and Bioenergy 2005;28: 87–93.

[34] Baiju B, Naik MK, Das LM. A comparative evaluation of compression ignition engine characteristics using methyl and ethyl esters of Karanja oil. Renewable Energy 2009;34:1616–21.
[35] Sarin R, Sharma M, Sinharay S, Malhotra RK. Jatropha–Palm biodiesel blends: an optimum mix for Asia. Fuel 2007;86:1365–71.
[36] Mittelbach M, Remschmidt C. Biodiesel: The Comprehensive Handbook. Vienna: Boersedruck Ges. M.B.H.; 2004.
[37] Knothe G, Matheaus AC, Ryan III TW. Cetane numbers of branched and straight chain fatty esters determined in an ignition quality tester. Fuel 2003;82:971–5.
[38] Karmakar A, Karmakar S, Mukherjee S. Properties of various plants and animals feedstocks for biodiesel production. Bioresource Technology 2010;101:7201–10.
[39] Raheman H, Ghadge SV. Performance of compression ignition engine with mahua (*Madhuca indica*) biodiesel. Fuel 2007;86:2568–73.
[40] Ramadhas AS, Muraleedharan C, Jayaraj S. Performance and emission evaluation of a diesel engine fueled with methyl esters of rubber seed oil. Renewable Energy 2005;30:1789–800.